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polarizabilities of a spherical target. In addition, precise positioning of the Rx assembly has been achieved via position inversion algorithms based solely on the data acquired from the receivers during the "on-time" of the primary field. Pedemis

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solution. In this paper, the Pedemis instrument is introduced along with its operation protocols, initial data results, and current status.

Pedemis: a Portable Electromagnetic Induction Sensor with Integrated Positioning

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Pedemis (PortablE Decoupled Electromagnetic Induction Sensor) is a time-domain handheld electromagnetic induction (EMI) instrument with the intended purpose of improving the detection and classification of UneXploded Ordnance (UXO). Pedemis sports nine coplanar transmitters (the Tx assembly) and nine triaxial receivers held in a fixed geometry with respect to each other (the Rx assembly) but with that Rx assembly physically decoupled from the Tx assembly allowing flexible data acquisition modes and deployment options. The data acquisition (DAQ) electronics consists of the National Instruments (NI) cRIO platform which is much lighter and more energy efficient that prior DAQ platforms. Pedemis has successfully acquired initial data, and inversion of the data acquired during these initial tests has yielded satisfactory polarizabilities of a spherical target. In addition, precise positioning of the Rx assembly has been achieved via position inversion algorithms based solely on the data acquired from the receivers during the "on-time" of the primary field. Pedemis has been designed to be a flexible yet user friendly EMI instrument that can survey, detect and classify targets in a one pass solution. In this paper, the Pedemis instrument is introduced along with its operation protocols, initial data results, and current status.

Keywords: EMI, UXO, Pedemis, quasistatic, vector receiver, sensitivity, handheld, discrimination, multitarget

1. INTRODUCTION

The identification of buried unexploded ordnance (UXO) and its discrimination from harmless clutter constitute a challenging problem that requires sophisticated sensing instruments[1, 2] and careful data modeling. In the Unites States alone, more than eleven million acres of land and many underwater sites are contaminated with the decades long remediation cost in the ten's of billions of dollars[3]. A wide range of different sensing technologies is being used or is in development for detecting and discriminating UXOs. Among these technologies, metal detectors have been identified as one of most promising technologies for detection as well as classification of subsurface metallic objects. There are two types of metal detectors. One, that is called magnetometers, detects anomalies in the earth's magnetic field caused by ferrous (iron-based) objects[4, 5]. The other, known as electromagnetic induction (EMI) sensing, transmits an electromagnetic field that can lead to the detection of both ferrous and non-ferrous metals. In this EMI frequency regime, displacement currents $\partial \overline{D}/\partial t$ are negligible relative to conduction current. The primary magnetic field penetrates inside the object to some degree and induces eddy currents within it. In return the induced currents produce secondary or scattered field outside that are measured by a receiver. Since these sensors can sense UXOs, they can detect everything else metallic in close proximity. Therefore, current discrimination techniques have great difficulties in distinguishing UXO from non-UXO metallic debris, found at most UXO sites. The high costs of excavating all geophysical anomalies are well known and are one of the greatest impediments to efficient clean-up of UXO contaminated lands at DoD and DoE sites. Innovative discrimination and classification techniques that can reliably distinguish between hazardous UXO and non-hazardous metallic items are required.

In order for these EMI metal detectors to penetrate the ground they must employ very low electromagnetic frequencies, ranging from tens of Hz to around one hundred kHz. As a consequence, it is not possible to image subsurface objects clearly due to the long wavelengths in the magnetoquasistatic regime. Instead, one must analyze recorded responses in

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search of some kind of telltale content or signature. This limitation is magnified by the low spatial diversity of the data: Many measurements involve only one component of the secondary field at each one of a limited set of points, and usually at only one instrument altitude. The forward models used for data analysis must be complete enough to provide reasonable estimates of the location and orientation of a target and at the same time a reliable characterization of its properties. It is also desirable that they be fast enough to produce results in something approaching real time.

Discrimination of unexploded ordnance (UXO) is achieved by employing forward models to extracting physics-based electromagnetic parameters from geophysical data acquired over subsurface anomalies and using these parameters as inputs to either human experts or statistical classification methods which determine the likelihood that the target is, or is not, a UXO. In past years, various simple parametric modeling methods have been developed and applied to UXO discrimination problems using monostatic electromagnetic induction (EMI) data. Studies show that there is a need for high-quality vector data and rigorous forward modeling approaches to achieve a high probability of UXO discrimination. In addition to advances in hardware, models that can make use of the amount of high quality data produced by advanced EMI instruments are also needed. Current models include the dipole model [6] and more rigorous models such as the Joint Diagonalization (JD) method [7], Orthonormalized Volume Magnetic Source Method (ONVMS) [8, 9], NSMC [10–18], and analytical models [19–25]. Results from an analysis of initial lab data using the standard dipole model are given in Sec. 5.

Multi-axis sensors have achieved excellent discrimination performance at recent ESTCP demonstration sites such as Camps Beale and Butner [26, 27] when compared to older single axis sensors such as the Geonics EM63. At many DoD sites, however, terrain and/or vegetation prohibit the use of cart mounted EMI sensors such as the MetalMapper [28] and TEMTADS [29]. More portable instruments have recently been deployed such as the MPV2 [30], and the "Mini"-TEMTADS (MR-201165 [31]). However, these sensors also have drawbacks which need to be addressed in order to achieve a single system that is both portable and advanced enough to allow one instrument to survey, detect, and discriminate, even in difficult cases to avoid later reinterrogation or needless excavation.

The new Pedemis (PortablE Decoupled Electromagnetic Induction Sensor) sensor[32] (see Figs. 1 and 2 and Sec. 2) has been designed to be a flexible yet user friendly EMI instrument that can survey, detect and classify targets in a one pass solution. It accomplishes this by having several deployment modes (made possible by its decoupled geometry) as well as real time feedback during anomaly interrogation. Pedemis does not suffer from utilizing a complex, external, corded positioning system, but instead an integral positioning system. It is not held by the operator during data collection, and the control electronics are much lighter and consume less power than other portable EMI instruments. As well, Pedemis is carried, not wheeled thus giving it more deployment options in challenging and/or vegetated sites. It has many more Tx/Rx combinations for greater data diversity, and a flexible user interface which will provide real-time feedback to the user.

This paper introduces Pedemis, currently in the final stages of fabrication, and is organized as follows: Sec. 2 introduces the Pedemis instrument and data collection capabilities, Sec. 3 details the system used to infer the position of the Rx assembly near the Tx coils, Sec. 4 describes our method to remove instrument background noise from the data, Sec. 5 describes initial data acquired at G&G Sciences laboratory, all followed by a conclusion.

2. PEDEMIS INSTRUMENT

Pedemis is a flexible platform with two separate components: a square transmitting array consisting of nine coplanar 40cm TEMTADS size Tx coils [29], and a detachable 3×3 planar array of vector receivers (each receiver a reproduction of the MPV2 receivers [30]). The receivers can either be placed to collect static data or moved around above or near the transmitting coils to obtain dynamic data (see Fig. 1). Both of these components can be affixed to a cart for larger scale detection surveys. Pedemis can also be carried by two people in a stretcher-type arrangement for cued interrogation even in rugged and/or challenging terrain. In summary, the following deployment modes will be considered and evaluated during this project:

1. Man-Portable Detection Mode (Rx units temporarily attached Tx array and both carried together)

2. Cued Interrogation Mode (receivers detached, transmitters stationary [with or without cart])

3. Carted Mode (relative geometry fixed)

4. Superposition Mode (receivers stationary, transmitters moved around so that Tx fields from adjacent locations can be summed to simulate the advantages of a single larger sensor)
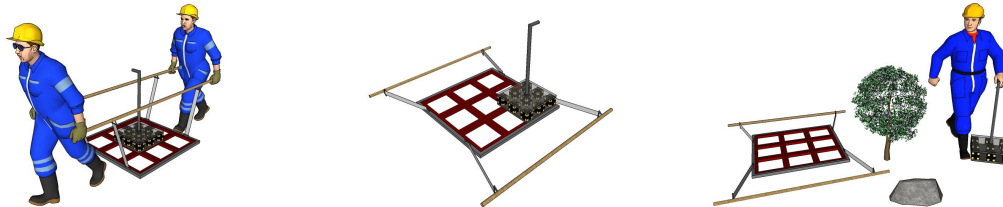
Figure 1: Conceptual design of the proposed sensor. Flexible modes of operation allow either cart mounted or man portable operation, static or dynamic data acquisition. This bistatic configuration allows greater positioning accuracy, improved depth detection, and deployment in difficult terrain. The nine red squares correspond to the Tx coils, while the receiver array is located on top of the Tx coils in the center figure.

Exploitation of bistatic measurements benefits significantly from precise positioning of the Rx unit relative to the Tx array. To this end, a novel beacon positioning system is implemented, with the goal of attaining subcentimeter level local relative positioning of the receiver coil assembly (see Sec. 3). The receivers detect the primary magnetic field during the "on" time of the (stationary) transmitter. Combining the data from each of the transmitters allows precise positioning of the receiver cubes by detecting the powerful and well known primary fields. These same receiver cubes then collect EMI data during the transmitter "off" time. The Tx and Rx assemblies as well as the accompanying DAQ system is shown in Fig. 2 in their current (Nov. 2011) state.

Pedemis acquired initial laboratory data in the Fall of 2011 (see Sec. 5). These data showed that Pedemis and its control software could collect reasonable data over typical targets. This proof of principle also showed that the acquired data could be used to calculate the position of the Rx array over the Tx coils (see Sec. 3). As explained above, Pedemis uses the transmitted field as a beacon, and the Rx signals during "on time" are exploited to track the position of the Rx array, without the addition of any other positioning equipment.

With this physical design, Pedemis will have several operation modes that we will test out and refine as the project moves forward to standardized then live sites. The data collection protocols depend on whether it is being used for detection and/or cued interrogation, and what the data quality and indications are over each anomaly. The detection mode and successive branching options for data collection with Pedemis are:
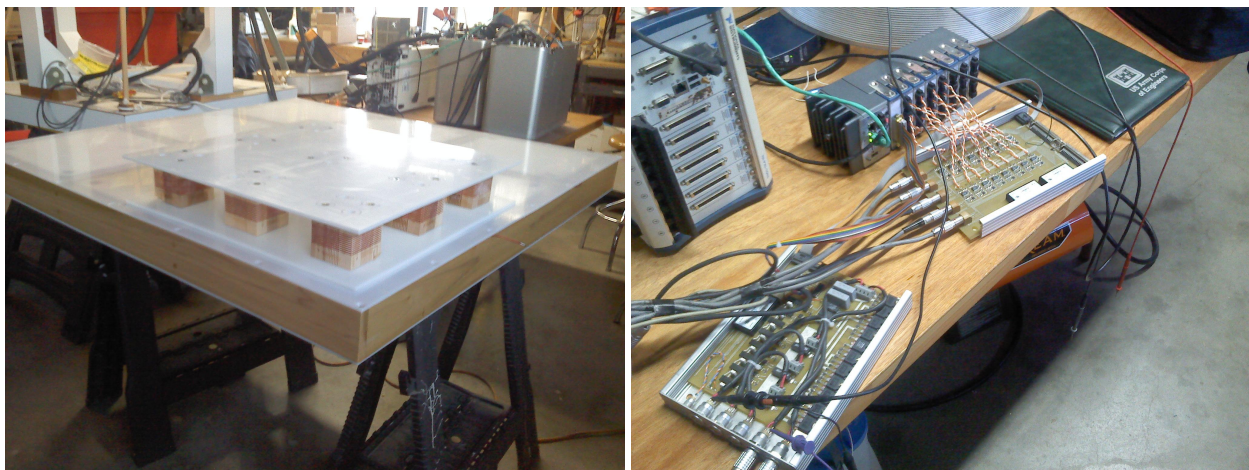

Figure 2: The Pedemis sensor's Tx and Rx arrays (left). The NI cRIO based control system with transmitter and filter boards (right). The Tx and Rx arrays can be detached. This bistatic configuration allows greater positioning accuracy, improved depth detection, deployment in difficult terrain, and flexible exploration of responses in the vicinity of the rig without relocating it.

- **Detection Mode –** Data is acquired at 10 samples per second as Pedemis is transported over the ground. A plot of the z-component of the magnetic field will be displayed in real time on controlling device to facilitate anomaly detection. During this time, the Rx array is centered and stationary on the Tx array.

- **Cued Interrogation Mode #1 –** This mode directly follows a detection. Pedemis is set down centered over the anomaly with the Rx array still in a centered, fixed position. A static data shot using all nine Tx and nine Rx coils in this configuration is then taken. This data shot will take around 30 seconds. Depending on the results of this data, users will follow one or more of the following three courses of action:

  1. *Enter Cued Interrogation Mode #2: move Rx unit to seek widespread multiple targets.*
  2. *Enter Cued Interrogation Mode #3: move Rx and/or Tx units to gain maximum registration of a deep target.*
  3. *Resume Detection Mode*

- **Cued Interrogation Mode #2 (for multiple and/or widespread targets) –** The Rx array will be positioned near each of the four corners of the Tx array in sequence for four 30 second data shots. This mode provides an equivalent 6x6 array of vector magnetic field values from 9 independent transmitters over a 1.2m square area. Based on real-time visualization of this data, the operator then has the option of moving the Rx array off to the side of the Tx array, pursuing any targets that are indicated there.

- **Cued Interrogation Mode #3 (for deep targets) –** This cued interrogation mode is used if deep targets seem to be present, but the data is not of sufficient SNR to make a reliable classification of the target. There are two options, not mutually exclusive:

  1. Longer signal stacking: the Rx array is left in the center of the Tx array (as in detection and cued #1 modes), for longer data acquisition in order to integrate more samples and thus increase SNR for deep targets. This data shot may take up to 5 minutes, depending on the desired SNR.
  2. Superposition mode: For a chosen Rx array location, the Tx array may be moved over adjacent positions. This allows summation of the results, for simulation of interrogation by a single, larger sensor.

As Pedemis is deployed to APG and live sites, the determination of which data protocol to follow will be made by expert users. The goal is to systematize the decision process into computer algorithms before Pedemis is udes by third parties.

Locata for geolocationing One persistent problem for EMI sensors in vegetated terrain is that GPS signals are not reliable. For Pedemis and other human portable EMI sensors, this has been a difficult hurdle for detecting and reacquisition (for example, ropes were used at Camp Beale). We will investigate using hardware based on the Locata "GPS 2.0" concept [33] for acquiring a global position, or geolocation, for Pedemis. The Locata system requires substations at known GPS locations to send out supplementary RF signals to Locata enabled GPS receivers. These RF signals can position the Locata enabled GPS receiver down to the centimeter level among trees or even indoors. Overall, GPS in various enhancements and precision levels will be evaluated at least for gross positioning of the Tx array, relative to which the beacon processing can provide precise Rx array location.

3. POSITIONING SYSTEM OF PEDEMIS

The Rx array on Pedemis is not held in a fixed geometry relative to the Tx array except as noted in Sec. 2 for cued interrogation mode #1. As a result, the position of the Rx array must be retrieved in order for data shots taken at different Rx array positions to be be meaningful. This position of the Rx array is found on Pedemis by a beacon positioning approach, an approach first conceived in our MR-1537 GEM-3$\mathscr{D}^+$ project and continued in MR-1443: MPV and MR-201005: MPV2.

The beacon positioning concept relies on the capability of the receivers to measure the strength of the primary field when each transmitter is being energized. After these data from the "on" time of the transmitter are recorded, the receivers then collect EMI data from the "off" time of the transmitters. Given these "on" time data, the geometry of the transmitters, and a record of the current in the energized transmitter, it is possible to calculate where the Rx array is in 3D space to under 1cm accuracy when the Rx array is within 2 meters of the Tx array.

We modeled the Pedemis beacon positioning system in order to predict how accurate we could expect the calculated position to be. For these results, a point receiver is assumed, though elsewhere [] we have investigated how close the receiver must be to the transmitters before one must model the receivers as surfaces or volumes. On the other hand, the transmitters were modeled as square N-turn line current sources using the Biot-Savart Law. Figure 2 shows an example of the Rx array above a model of the Tx array with the closest receiver at least 10cm away from the Tx coils.

Using our simulation as a sanity check, if we use all four expected Rx array locations (as in cued interrogation mode #2, see Sec. 2), there is essentially only numerical error on the order of machine precision for the inverted position of the Rx array.

After these types of checks, we also made sure targets under the Tx array would not distort the primary field sufficiently to degrade the "on" time measurements and produce a false position. To this end, we added a simulated 10cm sphere only 10cm below the center of the Tx array to see what effect it would have on the primary field and thereby the inverted Rx array position. Figure 3 shows the log10 positional error in the inverted Rx array location when the Rx array is 10cm above the Tx array and the sphere is present. Even though the presence of the sphere caused up to 1.5% perturbation of the
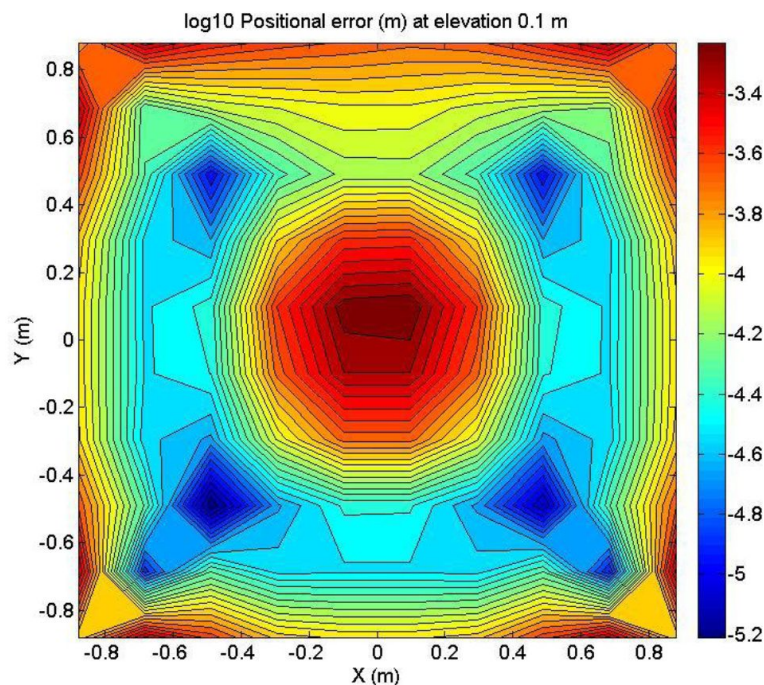

Figure 3: Pedemis beacon target induced error from a sphere placed under the Tx array.

primary field for some Tx/Rx combinations, the overall position of the Rx array was accurate to within less than 1mm.

We applied the algorithms developed during the simulation phase to the initial data collected in November 2011 in Grand Junction, CO (see Sec. 5). For the data shot #3 in Sec. 5, the MPV2 sensor head was left in one location (at the bottom right corner of the Tx array) while all nine transmitters fired in turn (see Fig. 5). For this case, with the Rx array directly over the (undamped) transmitters, the error in the inverted Rx array position was 2-3mm, which is on the order of our physical measurement expected error.

Our final test corresponding to data shot #4 in Sec. 5 tested whether the position of the Rx array could be inverted for even when the Rx array was positioned outside the Tx array. Figure 4 shows the inverted position of the Rx array using our algorithms. In this case as well, the inverted position was withing half a centimeter which is within the manual positioning and measurement error.

These results are encouraging in that they suggest that the beacon positioning system and algorithms can invert for the position of the Rx array when the Rx array is within a meter of the Tx array. The accuracy appears to be within 1cm and in most cases on the order of a few millimeters.
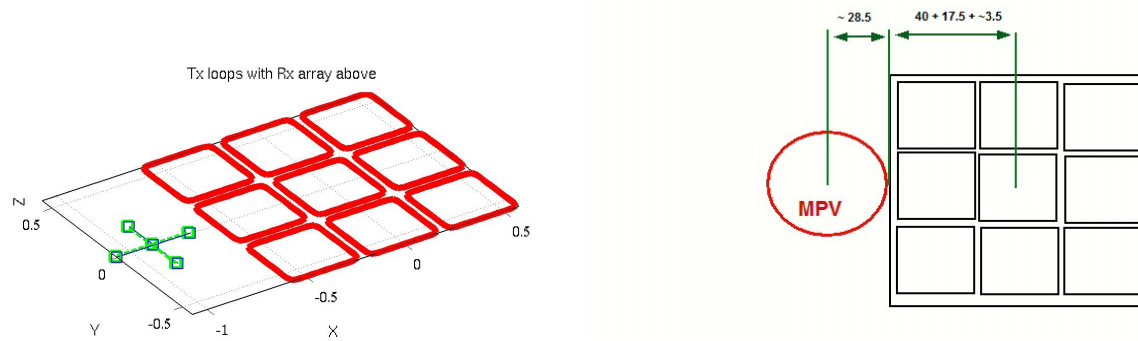
Figure 4: Pedemis Beacon Inversion #2 for the case of the MPV2 outside and to the left of the Tx array. No target was present and the inverted position was within 0.5cm of the measured position.

4. BACKGROUND SUBTRACTION

All EMI instruments generally have to account for background noise when acquiring data or the results may be poor or corrupted. With all prior EMI instruments, the transmitter(s) and receiver(s) have been in a fixed geometry with respect to each other, so acquiring a background shot was a relatively simple matter or finding a quiet location and acquiring a data shot. Because the Tx and Rx arrays on Pedemis are not in a fixed geometry, the "background" is not as simple to acquire and remove from the data. Background due to instrument noise is one type of background that we would definitely like to remove from Pedemis data. But if the Rx array is at all moved off from a prior location, the instrument noise will change dramatically mainly because the Tx coils are so close to the receivers. These Tx could can act like targets themselves, but their influence in the EMI data is considered instrument noise and is undesirable.

Our plan to remove this noise could center on simply taking thousands of measurements and interpolating between them in the 6-space consisting of Pedemis's 3D location in space and its current 3 Euler angles. Not only is that laborious, but trying to get that many measurements, including in the 2 meters outside the Tx array could take years even on an automated platform like the ERDC test stand.

Instead, we plan to reproduce the response from the Tx coils (included as part of instrument noise or instrument background) using an equivalent source approach similar to the NSMS method. These equivalent sources will be found from a much smaller set of normal background measurements at known locations. Once this set of sources is known, the time domain response from the coils (as represented by the sources) can be quickly calculated anywhere in space. The location of the Rx array will be known from the Pedemis beacon type positioning as described in Sec. 3. Any future background type measurements in the air will be added to the training routine for the equivalent sources and their accuracy will be improved. This instrument background subtraction routine will be built into Pedemis so that any data collected by Pedemis will have this instrument noise removed before recording the data. Note that this solution for this instrument noise does not address the issue of gelogical noise in the EMI due to the soil.

5. PEDEMIS INITIAL DATA

We were able to collect initial proof of concept data outside of G&G Sciences office in Grand Junction, CO in November, 2011. Pedemis was not fully fabricated, but we were able to perform a test using some of the MPV2 Rx cubes and electronics. We used the Pedemis cRIO based system with the LabVIEW VIs to control the boards and sample the output of the Rx channels after the filter board (see Fig. 2). The core functionality of these VIs will be improved but the core control logic is complete.

Figure 5 show the data acquisition setup and process at Grand Junction, CO in November, 2011. Data was collected (a "shot") at 5 MPV2 positions over the Tx array with all 9 transmitters firing in turn. In terms of orientation, the MPV2 handle is pointing in the negative *y* direction. Four total data shots were collected:

Figure 5: Initial data setup in Grand Junction CO in November, 2011. The MPV2 receivers were used as the Pedemis Rx cabling was incomplete.

1. A background shot

2. A shot over a 4 inch steel sphere. The sphere was located at depth 26 cm (to nearest point on sphere) under the corners of the four upper left transmitters.

3. Positioning test shot with no target. For this shot, the MPV2 sensor head was left in one location (at the bottom right corner of the Tx array) while all nine transmitters fired in turn. This was to test the positioning algorithms in Sec. 3 with no target present.

4. Positioning test shot with no target. This time, the MPV2 sensor head was outside the Tx array to the left (see Sec. 3).

The initial data was analyzed for satisfactory SNR and reasonableness in our lab. Figure 6 shows the raw data from the 5 MPV2 receivers situated in the top left corner of the Tx array and the center transmitter firing. As expected, the z-components of the received magnetic field are more noisy than the x or y components due to the open terminals at the non-energized transmitter terminals. Note that we integrated and averaged one hundred 10Hz measurements for these data. Using our Gauss-Newton dipole inversion routine [6, 34], we get the polarizabilities shown in Fig. 7 using only the x and y components of the received magnetic field.

6. CONCLUSION

Pedemis is mostly fabricated as of March 2012. The remaining hardware and cables will be fabricated before summer 2012 as part of the last year of SERDP MR-1712. The Tx and Rx assemblies are designed and fabricated. The DAQ electronics consists of the National NI cRIO platform which is much lighter and more efficient that prior DAQ platforms. Software to control the cRIO DAQ process has been written in NI's LabVIEW. This software has been used to successfully acquire data initial over a sphere as shown in Sec. 5. Inversion of the data acquired during these initial tests has yielded satisfactory polarizabilities of the spherical target. In addition, precise positioning of the Rx assembly has been achieved via position inversion algorithms based solely on the data acquired from the receivers during the "on-time" of the primary field (see Sec. 3). Pedemis sports flexible deployment and operational modes in a one pass, flexible solution to survey, detect and discriminate UXOs based on high quality multi-axis data and real time data based feedback.
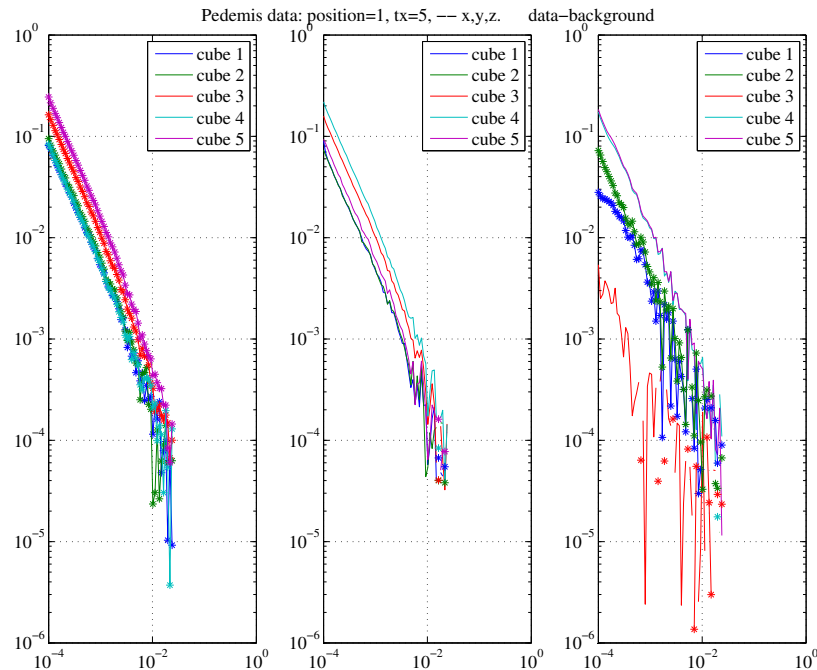
ACKNOWLEDGMENTS

Figure 6: Example data from Pedemis. Raw data from the 5 MPV2 receivers situated in the top left corner of the Tx array and the center transmitter firing.
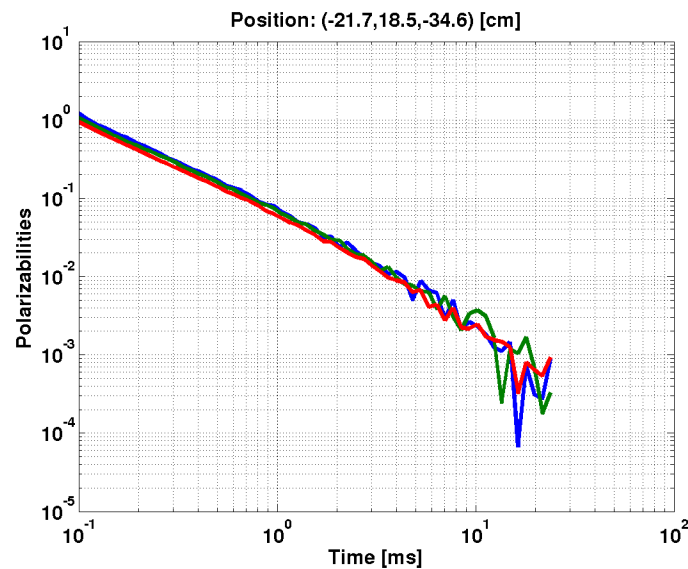

Figure 7: Polarizabilities from data in Fig. 6. These were calculated using only the *x* and *y* components of the received magnetic field due to the z-component being noisy due to the Tx open circuits.

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